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of permanent magnets 7 provided on the rotor 2a. A motor and a magnetic bearing are formed between the rotor 2a equipped with the permanent magnet 7 and the stator 3a. Also, magnetic bearings are formed between the rotor 2a and the stator 3a.

The rotors 2a and 2b are formed from main body sections composed of a magnetic material, and provided on a rotor shaft 8 composed of a magnetic material at locations spaced a specified distance from one another. The main body sections forming the rotors 2a and 2b and the rotor shaft 8 are both formed from a magnetic material. Therefore, the main body sections composing the rotors 2a and 2b also define part of the rotor shaft 8. Among the rotors 2a and 2b, the plural permanent magnets 7are disposed around a peripheral surface of the rotor 2a in a manner that their magnetic polarities are alternately inverted (i.e., N, S, N, S,...) along a direction of the periphery of the rotor 2a. The permanent magnets 7 include permanent magnets with N-polarities being exposed on their surfaces and permanent magnets with S-polarities being exposed on their surfaces that are alternately disposed. The rotors 2a and 2b may preferably be formed from stacked silicon steel plates in order to prevent eddy currents.

The stators 3a and 3b are disposed adjacent to external peripheral surface of the rotors 2a and 2b in a manner to encircle the peripheral surfaces of the rotors 2a and 2b, respectively. First stator windings 5a and 5b are wound around the stators 3a and 3b, respectively, to generate two-pole levitation control magnetic fluxes $\phi F$ to controllably levitate the rotors 2a and 2b. A second stator winding 6 is provided on the stator 3a adjacent to the first stator winding 5a to provide a rotation magnetic field $\phi K$ for the rotor 2a.

The direct current magnetic field generation device 4 is provided between the stators 3a and 3b. The direct current magnetic field generation device 4 generates a magnetic flux $\phi D$ that is radially distributed and

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oriented from the rotors 2a and 2b to the stators 3a and 3b. In one embodiment, the direct current magnetic field generation device 4 is formed from permanent magnets P that are disposed in a central area between the stators 3a and 3b. The permanent magnets P generate direct current bias magnetic fields between the rotors 2a and 2b and the stators 3a and 3b. The number of the permanent magnets P that function as the direct current magnetic field generation device 4 for generating the bias magnetic fluxes is not particularly restricted. However, the greater the number of bias magnetic fluxes within the gap, the more the required levitation current is reduced. Accordingly, the number of the permanent magnets P may preferably be increased as many as possible. The stators 3a and 3b may also be formed from stacked silicon steel plates.

The number of the magnetic poles of the rotor 2a and the number of slots of the stator 3a are not particularly restricted. Any number of the magnetic poles or the slots may be acceptable to the extent that they can compose a PM motor. However, in a preferred embodiment, the number of the magnetic poles may be 6 or more, and the number of the slots may be 9 or more. In the embodiment shown in the figure, six (6) magnetic poles and twelve (12) slots are provided. In an alternative embodiment, the PM motor described above may have a stator with a slot-less structure.

Operations of the magnetic levitation motor will be described with reference to Figs. 1 and 2 and Figs. 3 and 4.

Fig. 3 shows a system of coordinates of the rotor. In Fig. 3, a rotation center of the stators 3a and 3b is defined at 0, a horizontal axis is defined as an x-axis and a vertical axis perpendicular to the x-axis is defined as a y-axis. When a rotary coordinate fixed on the stators 3a and 3b is θ, the angular speed of the rotors 2a and 2b is ω, and time is t, each of the stators 3a and 3b is disposed at an angular speed θ from the y-axis. When the y-axis is set at



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time t = 0, the position of the rotors 2a and 2b after t seconds is obtained by a formula ωt/M.

Figs. 4 (a) – 4 (c) show relations between magnetic fluxes of the stators and the rotors and time. Fig. 4 (a) shows time-wise changes in the magnetic flux density Br of the bias magnetic flux generated by the permanent magnets of the rotors and the direct current magnetic field generation device. Fig. 4 (b) shows time-wise changes in the magnetic flux density Bsm generated by the second stator winding in the gap between the stators and the rotors. Fig. 4 (c) shows time-wise changes in the magnetic flux density Bsb generated by the first stator winding.

In the magnetic levitation motor 1, current is conducted through the first stator windings 5a and 5b for generating a levitation force so that magnetic fields are created by the first stator windings 5a and 5b in a manner shown in Fig. 4 (c). Also, current is conducted through the second stator winding 6 for generating a rotation force so that magnetic fields are created by the second stator winding 6 in a manner shown in Fig. 4 (b). As a result, the magnetic levitation motor 1 magnetically floats and rotates as a motor.

In this manner, current is conducted through the first stator windings 5a and 5b to generate the magnetic flux density Bsb, and current is conducted through the second stator winding 6 to generate the magnetic flux density Bam, to thereby create a magnetic levitation and a rotation independently from one another. The generation of independent magnetic levitation and rotation forces is logically analyzed. In order to make the logical analysis, the following assumptions (1) through (6) are made.

(1) Electric current is continuously distributed along the stators 3a and 3b.

(2) The motor is in a constant rotation and under a constant thrust load (the gravity and the like).

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(3) The rotor 2a forms a magnetic flux density having a rectangular waveform by the permanent magnets, and this magnetic flux density does not cause an eccentric force.

(4) The center of the rotors 2a and 2b concurs with the center of the stators 3a and 3b without an eccentricity.

(5) The bias magnetic flux is constant and radially distributed.

(6) The current conducted through the second stator winding 6 for generating a rotation magnetic field does not cause any armature counter action.

Under the assumptions described above, the magnetic flux density Br by the bias magnetic flux generated by the rotor 2a and the permanent magnets 7 is given by Formula 1 as follows:

[Formula 1]

$$Br = \begin{cases} B_0 + B_1 \\ \cdots\left(\frac{\omega t}{M} + \frac{2\pi(i-1)}{M} - \frac{\pi}{2M} \sim \frac{\omega t}{M} + \frac{2\pi(i-1)}{M} + \frac{\pi}{2M}\right) \\ B_0 - B_1 \\ \cdots\left(\frac{\omega t}{M} + \frac{2\pi(i-1)}{M} + \frac{\pi}{2M} \sim \frac{\omega t}{M} + \frac{2\pi(i-1)}{M} + \frac{\pi}{2M}\right) \end{cases}$$

Where,

$B_0$ : Gap magnetic flux density by the bias magnets

$B_1$ : Wave height of the magnetic flux density by the permanent magnet of the rotor

$B_2$ : Wave height of the magnetic flux density by the motor winding

$B_3$ : Wave height of the magnetic flux density by a position control winding

$\theta$ : Rotary coordinate of the magnetic flux density by a position control winding

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$\psi$ : Phase difference between the magnetic flux by the armature winding and the rotor

$\phi$ : Phase angle of the magnetic flux by the position control winding

$\omega$ : Angular speed of the rotor

t : Time

M : Pole pair number (=1, 2, 3, ...)

i : Natural number

To simplify the calculation, the curve of the magnetic flux density Br is assimilated to a sine wave. As a result, the magnetic flux density Br can be presented by Formula 2 as follows:

[Formula 2]

$$Br = B_0 + B_1 \cos (M\theta - \omega t)$$

The magnetic flux density Bsm generated by the second stator winding 6 between the rotor 2a and the stator 3a is given by Formula 3 as follows:

[Formula 3]

$$Bms = B_2 \cos (M\theta - \omega t - \psi)$$

The magnetic flux density Bsb generated by the first stator windings 5a and 5b is given by Formula 4 as follows:

[Formula 4]

$$Bsb = B_3 \cos (\theta - \phi)$$

Therefore, the magnetic flux density Bg that is generated in air gaps between the rotors 2a and 2b and the stators 3a and 3b is given by Formula 5 as follows:

[Formula 5]

$$Bg = Br + Bsm + Bsb$$

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When the radius of the rotors 2a and 2b is r, an air gap between the rotors 2a and 2b and the stators 3a and 3b is g, the axial length of each of the rotors 2a and 2b is l, and a minute angle is dθ, a minute volume ΔV of the air gap is given by Formula 6 as follows:

[Formula 6]

$$\Delta V = r\, l\, g\, d\theta$$

Magnetic energy ΔW stored in the minute volume ΔV is given by Formula 7 as follows:

[Formula 7]

$$\Delta W = \frac{B_g^2}{2\mu_0}\Delta V = \frac{B_g^2}{2\mu_0} r\, l g\, d\theta$$

Accordingly, a radial force dF along the radial direction is given by Formula 8 below with a virtual displacement of the magnetic energy stored in the minute volume of the gap:

[Formula 8]

$$dF = \frac{\partial \Delta W}{\partial g} = \frac{B_g^2}{2\mu_0} r l d\theta$$

Forces Fx and Fy generated along the x-axis and the y-axis are calculated by Formula 9 and Formula 10 presented below, respectively, by integrating an x-direction component and a y-direction component of the force dF in Formula 8 along the entire periphery of the gap for a given value of θ.

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[Formula 9]

$$Fx = \int_V dF \cos\theta$$

$$= \int_0^{2\pi} \frac{B_g^2}{2\mu_0} rl \cos\theta \, d\theta$$

$$= \frac{lr}{2\mu_0}\Big[ \frac{B_0 B_1}{2} \int_0^{2\pi} \cos\{(M-1)\theta - \omega t\} d\theta$$

$$+ \frac{B_0 B_1}{2} \int_0^{2\pi} \cos\{(M-1)\theta - (\omega t + \psi)\} d\theta$$

$$+ 2 B_0 B_3 \pi \cos\phi$$

$$+ \frac{B_1 B_3}{2} \int_0^{2\pi} \cos\{(M-2)\theta - (\omega t - \phi)\} d\theta$$

$$+ \frac{B_2 B_3}{2} \int_0^{2\pi} \cos\{(M-2)\theta - (\omega t + \psi) + \phi\} d\theta \Big]$$

[Formula 10]

$$Fy = \int_0^{2\pi} \frac{1}{2\mu_0} B_g^2 rl \sin\theta \, d\theta$$

$$= \frac{lr}{2\mu_0}\Big[ \frac{B_0 B_1}{2} \int_0^{2\pi} \sin\{(1-M)\theta + \omega t\} d\theta$$

$$+ \frac{B_0 B_1}{2} \int_0^{2\pi} \sin\{(1-M)\theta + (\omega t + \psi)\} d\theta$$

$$+ 2 B_0 B_3 \pi \sin\phi$$

$$+ \frac{B_1 B_3}{2} \int_0^{2\pi} \sin\{(2-M)\theta + \omega t - \phi\} d\theta$$

$$+ \frac{B_2 B_3}{2} \int_0^{2\pi} \cos\{(2-M)\theta + (\omega t + \psi) - \phi\} d\theta \Big]$$

When M ≥ 3, $Fx$ and $Fy$ are given by Formula 11 and Formula 12, respectively, as follows:

[Formula 11]

$$Fx = \frac{B_0 B_3 lr\pi}{\mu_0} \cos(\phi)$$

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[Formula 12]

$$Fy = \frac{B_0 B_3 l r \pi}{\mu_0} sin(\phi)$$

Accordingly, it is understood that, without regard to the rotation angle of the rotors 2a and 2b, a constant levitation force is obtained. The levitation force in the x-direction in Formula 11, the levitation force in the y-direction in Formula 12 and the magnetic flux density of the permanent magnet of the rotor 2a do not contain a member of the magnetic flux density by the second stator winding 6 for generating a rotation magnetic field. Accordingly, it is understood that the magnetic levitation force is not influenced by the rotation magnetic field that is formed by the second stator winding 6.

On the other hand, a rotation torque T is given by Formula 13 as follows:

[Formula 13]

$$\begin{aligned} T &= \int_0^{2\pi} \frac{\theta \Delta W}{\partial \psi} \\ &= \frac{r\, lg\, M B_1 B_2 \pi}{\mu_0} sin\, M\psi \\ &+ \frac{r\, lg\, M B_1 B_2}{2\mu_0} \int_0^{2\pi} sin\{(M-1)\theta \\ &- M(\omega t + \psi) + \phi\} d\theta \end{aligned}$$



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When $M \geq 2$, the rotation torque T is given by Formula 14 as follows:

[Formula 14]

$$T = \frac{r \lg M B_1 B_2 \pi}{\mu_0} \sin M\psi$$

Accordingly, it is understand that the rotation torque T does not contain any member of the air gap magnetic flux density of the bias magnetic field generated by the direct current magnetic field generation device 4, or the magnetic flux density generated by the first stator windings 5a and 5b for generating the magnetic levitation force. Consequently, the rotation torque T is not influenced by the bias magnetic field or the levitation magnetic field.

The magnetic levitation motor described above so far is described and shown in the specification of Japanese Laid-open patent application HEI 10–355124 that is filed by the present applicant and has not yet been published. The magnetic levitation motor described above provides the following advantages:

(1) Since the magnetic bearing and the magnetic circuit of the motor are integrally formed, the overall size of the magnetic levitation motor becomes small, and the axial length can be shortened. As a result, the critical speed can be increased and a high speed rotation becomes possible.

(2) The magnetic levitation control is not affected by the load torque or the motor electric current, and a more stabilized levitation can be attained.

(3) The magnetic levitation control is not performed by the rotation magnetic field, and therefore a coordinate conversion is not required and the control system is simplified.

A homopolar type magnetic levitation motor needs at least 8 magnetic salient poles. However, the magnetic levitation motor in accordance with



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